SOME ASPECTS OF THE THERMAL ENERGY EXCHANGE ON THE SOUTH POLAR SNOW FIELD AND ARCTIC ICE PACK[1]

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ABSTRACT

Solar and terrestrial radiation measurements that were obtained at Amundsen-Scott (South Pole) Station and on Ice Island (Bravo) T–3 are presented for representative summer and winter months. Of the South Polar net radiation loss during April 1958, approximately 20 percent of the energy came from the snow and 80 percent from the air. The actual atmospheric cooling rate during that period was only about 1/6 of the suggested radiative cooling rate. The annual net radiation at various places in Antarctica is presented. During 1958, the South Polar atmosphere transmitted about 73 percent of the annual extraterrestrial radiation, while at T–3 the Arctic atmosphere transmitted about 56 percent. The albedo of melting sea ice is discussed. Measurements on T–3 during July 1958 indicate that the net radiation is positive on both clear and overcast days but greatest on overcast days. Refreezing of the surface with clear skies, as observed by Untersteiner and Badgley, is discussed.

1. INTRODUCTION

The elliptical orbit of the earth brings it about 3 million miles farther from the sun at aphelion than at perihelion; consequently, during midsummer, about 7 percent less solar radiation impinges on the top of the Arctic atmosphere than on the Antarctic atmosphere during a comparable period. This difference is enhanced as solar energy penetrates into both polar atmospheres. Absorption, scattering, and reflection of the solar rays gives each polar region its own particular radiation environment. There are also other notable differences between the heat budgets of these two areas; for example, the conduction of heat through the ice is distinctly different. Annually, heat from the Arctic Ocean is conducted upward through the thin ice pack to the relatively cold surface where the temperature averages about −20° C. In contrast, the flux of heat through the ice layers of central Antarctica is quite small. Because of the heat budget differences, the annual temperature near the North Pole is about 30° C. warmer than that at the South Pole. It is the purpose of this paper to discuss some aspects of the thermal energy budgets of these regions.

The data which are presented were obtained during the International Geophysical Year and later years at Amundsen-Scott Station, located within a mile of the geographic South Pole, and at Ice Island T–3, drifting in the Arctic Ocean. This Island was about 5 by 11 miles in size and about 52 meters thick (Crary et al. [2]) in 1953 when it drifted near 88° N., 100° W. In the years that followed, this it drifted southward and in July 1958 was located 79.5° N., 118° W.

Solar radiation measurements at both stations were obtained with Eppley pyranometers. The data are corrected for the temperature response of the instrument (MacDonald [11]) and are presented in the International Pyrheliometric Scale of 1956. At both stations, Beckman and Whitley (Gier and Dunkle type) radiometers were used to measure the combined solar and terrestrial radiation streams.

2. WINTER MONTH AT THE SOUTH POLE

With the exception of a few weeks of twilight, sunset at the time of the March equinox marks the beginning of 6 months of continuous darkness at the South Pole. During the first of the dark months, April, the temperature a few meters above the snow averaged −58° C. (1957–59)—the same as the average temperature during the entire dark period.

In April 1958 the long-wave radiation [2] from the snow surface averaged 229 ly. day^{-1} (table 1), while the atmospheric (back) radiation returned 76 percent of this energy (175 ly. day^{-1}) to the surface. The net radiation averaged −54 ly. day^{-1}.

[1] Paper presented at the International Antarctic Symposium at Buenos Aires, November 1959.

[2] Terrestrial radiation, with most of the energy between wavelengths of 3 to 30 microns.

TABLE 1.—*Thermal energy exchange at the snow surface, Amundsen-Scott (South Pole) Station, Antarctica*

	January 1958	April 1958	Annual 1958
Incident solar radiation (ly. day^{-1})*	770	0	266
Reflected solar radiation (ly. day^{-1})	674	0	218
Albedo (percent)	88		82
Snow surface radiation (ly. day^{-1})	440	229	301
Atmospheric (back) radiation (ly. day^{-1})	309	175	218
Return (percent)	70	76	72
Net radiation (ly. day^{-1})	−35	−54	−35
Thermal energy from snow (ly. day^{-1})		11	
Thermal energy from air (ly. day^{-1})		43	

*One Langley (ly.) equals one cal. cm.$^{-2}$

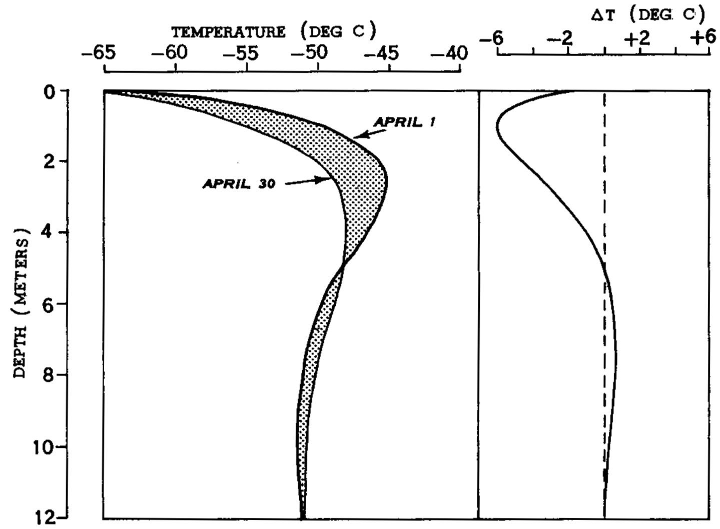

FIGURE 1.—Snow temperature profiles of April 1 and 30, 1958, and monthly temperature-change profile, Amundsen-Scott (South Pole) Station, Antarctica.

The total thermal energy in the top 12 meters of snow at the beginning and end of April 1958 was calculated, using the equation

$$Q=\int_0^{12} c\rho T dz \tag{1}$$

where c is the specific heat in cal. gm^{-1} deg.$^{-1}$ (List [9]), ρ is the density in gm. cm.$^{-3}$ (Giovinetto [4]), and T is the temperature (fig. 1) in °K. The calculations indicate that during the month heat was conducted to the surface at the rate of 11 ly. day^{-1}. This suggests that, of the net radiation loss during April, about 20 percent of the energy came from the snow and 80 percent from the air. During clear, cold periods at the South Pole the snow and air supply about equal amounts of energy to make up the surface radiation loss (Hanson [6]). Liljequist [8] found that with clear skies at Maudheim, along the coast of Antarctica, roughly 40 percent of the required energy comes from the snow and 60 percent from the air.

Some idea of the heat budget of the atmosphere during this period can be obtained from the airborne radiation measurements which were taken with Suomi airborne radiometers (Suomi et al. [14]). Data from the clear-sky flight on April 27, 1959 (fig. 2) indicate a radiative loss of 240 ly. day^{-1} at 50 mb. Assuming this loss is representative of April 1958, and adding the small amount of heat which was conducted from the snow (11 ly. day^{-1}), the net cooling rate from the surface to 50 mb. becomes 1.49° C. day^{-1}. This is about 6 times greater than the observed cooling rate (0.26°C. day^{-1}). Presumably, subsidence and advection provide the necessary energy to account for the discrepancy.

3. SUMMER MONTH AT THE SOUTH POLE

Even though the South Polar plateau receives more solar radiation at midsummer than any other area on earth, the temperature of the snow surface remains well below freezing. In January, the warmest month of the summer, the temperature averages near −27° C., and rarely exceeds about −17° C.

During January 1958, with continuous sunlight at the South Pole, the incoming solar (sun and sky) radiation averaged 770 ly. day^{-1}. Measurements indicate that, of this amount, 88 percent (674 ly. day^{-1}) was reflected from the snow, while the remainder (96 ly. day^{-1}) was absorbed. During the same period, the snow surface radiated 440 ly. day^{-1}, while the atmospheric (back) radiation returned 70 percent (309 ly. day^{-1}) of that energy. The net radiation averaged −35 ly. day^{-1}.

4. ANNUAL ENERGY EXCHANGE, ANTARCTICA

During the 6 months of sunlight at the South Pole, the solar radiation which was incident on the snow totaled 9.71×10^4 ly. The snow reflected 7.96×10^4 ly., indicating an average albedo of 82 percent for the sunlit period.

Unlike solar radiation, the emission of long-wave radiation by the snow is continuous throughout the year. During 1958, the snow surface radiation averaged 301 ly. day^{-1}, of which about 72 percent (218 ly. day^{-1}) was returned by atmospheric (back) radiation. This percentage is relatively unchanged from summer to winter even though the sky is much clearer during winter (fig. 3). With other things being equal, clear skies would certainly tend to lower this percentage. Apparently, a compensating factor is that the surface temperature inversion is more intense during winter; this would allow a greater return of the surface radiation.

The net radiation at the South Pole (2800 m.) averaged about −35 ly. day^{-1} during 1958. Liljequist [7] found an annual loss of 25 ly. day^{-1} at Maudheim, and Loewe [9] found a loss of 20 ly. day^{-1} at Port Martin. Both stations are located along the coast of Antarctica. Rusin [13] has reported an annual net radiation of −6 to −8 ly. day^{-1} at Mirny, another coastal station, and −19 to −22 ly. day^{-1}

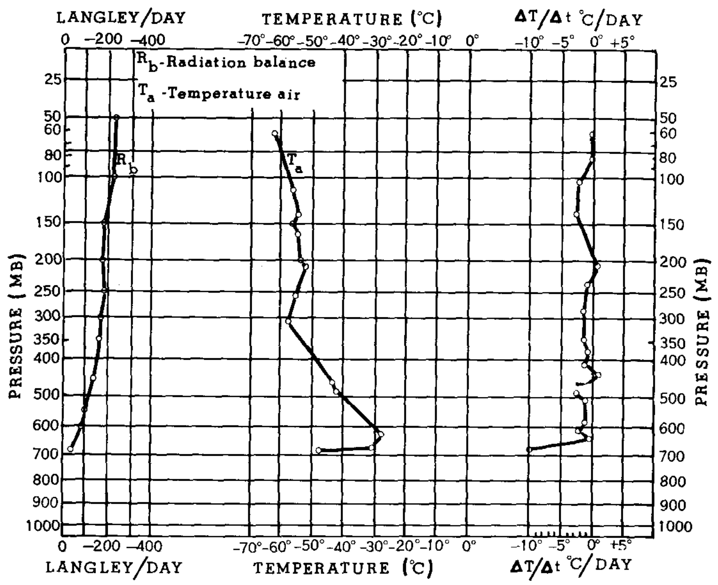

FIGURE 2.—Net radiation profile, temperature profile, and temperature-change profile computed from radiometersonde (Suomi et al. [14]) ascent at Amundsen-Scott (South Pole) Station, Antarctica, 0600 GMT April 27, 1959.

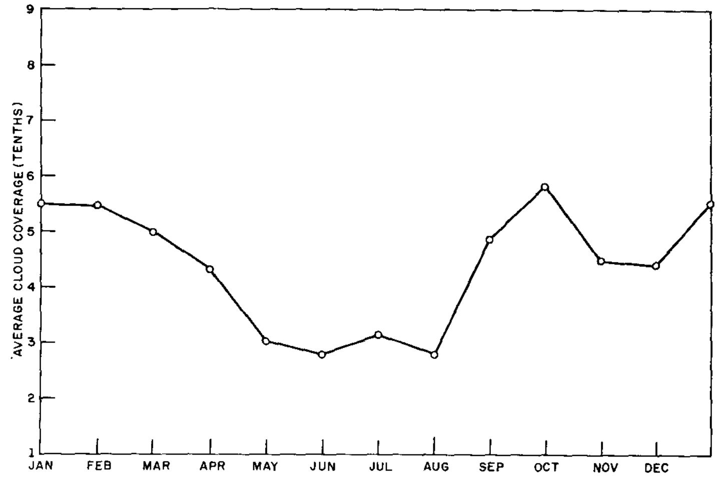

FIGURE 3.—Average cloud coverage during the period January 1957 through December 1960 at Amundsen-Scott (South Pole) Station, Antarctica.

at Pionerskaya (2700 m.) in the interior of eastern Antarctica. There is little doubt that, as a whole, the surface of Antarctica has a negative net radiation, although certain snow-free areas on the continent and portions of the Palmer Peninsula are probably positive. Considering the magnitude of the individual incoming and outgoing radiation streams, the slight variation of net radiation, as observed in Antarctica, seems rather remarkable.

5. ANNUAL ENERGY EXCHANGE, ARCTIC OCEAN BASIN

Although the elliptical orbit of the earth causes comparatively less midsummer extraterrestrial radiation in the Arctic, it also provides 9 additional days of sunlight at the North Pole each year compared to the South Pole. The net result is that during the course of their respective sunlit periods, equal amounts of solar energy impinge on the top of the North and South Polar atmospheres. This was pointed out by Milankovitch [12], who indicated that at both geographic poles the annual extraterrestrial radiation is of equal intensity, and, assuming a solar constant of 2.00 ly. min.$^{-1}$, totals 13.33×10^4 ly. during the year. This equality is not maintained as the solar rays penetrate the polar atmospheres, however. The previously mentioned measurements at the South Pole indicate that, annually, about 73 percent of the extraterrestrial radiation was incident on the snow surface. At Ice Island T–3, on the other hand, only about 56 percent of the extraterrestrial radiation [3] was incident at the surface during 1958. The fact that a smaller percentage of the extraterrestrial radiation reaches the surface in the Arctic may be due to a number of factors: possibly there are thicker cloud systems in the Arctic, the surface albedo is less in the Arctic, and the optical thickness of the Arctic atmosphere is greater because of the comparatively lower surface elevation of the Arctic. Precisely how these variables affect the amount of solar energy, incident on the Arctic and Antarctic, is difficult to determine without a better knowledge of the surface albedo and thickness of the cloud systems (Fritz [3]).

[3] Located at 79.5° N., the extraterrestrial radiation at T–3 totaled 13.81×10^4 ly. during 1958.

6. SUMMER MONTHS IN THE ARCTIC

The snow that covers much of the Arctic sea-ice in early spring is gradually melted during May and June. As a result, pools of melt water form on the ice floes in late June and remain during July and sometimes August. These pools aid in lowering the surface albedo during this midsummer ablation period. Sverdrup [15] has indicated that the albedo of melting Arctic sea-ice is between 60 and 65 percent. Recent Soviet investigations (Briazgin [1]) have shown a similar albedo value, 60 percent. The fact that pools of melt water on the floes lower the albedo is indicated by the results of an aerial albedo survey over the Arctic Ocean. This survey indicated that the albedo of melting ice with a maximum amount of puddling is about 46 percent (Hanson [5]).

Measurements on T–3 indicate that during July 1958 the incident solar radiation averaged 524 ly. day^{-1}. Assuming an albedo of 60 percent, the ice would have gained 210 ly. day^{-1}. Measurements also indicate that, with an average 6.7-tenths cloud coverage, the atmospheric long-wave radiation returned about 88 percent (578 ly. day^{-1}) of the 653 ly. day^{-1} which were emitted as long-wave radiation from the surface. This gives an average net radiation of +135 ly. day^{-1} during July.

Currently, one of the most important questions in polar heat-budget investigations is: How is the "surplus" thermal energy, available from radiative exchange, used in warming or melting the ice, evaporation, or warming the lower atmosphere? During the previously mentioned period, for example, the net radiation could have melted 58 cm. of surface ice, assuming a density of 0.9 gm. cm.$^{-3}$ and a latent heat of fusion of 80 cal. gm.$^{-1}$ The actual ablation was probably somewhat less, however, as a small amount of energy is lost in evaporation (Untersteiner and Badgley [16]), and possibly, as Fritz [3] and Yakovlev [17] have suggested, some energy may be lost to the atmosphere by turbulence. Because ablation, evaporation, and temperature profile measurements are not available, the heat and water budget during this important summer ablation period cannot be determined precisely.

An interesting observation regarding the heat budget was made by Untersteiner and Badgley [16] on Floating Ice Station "A":

> During the summer, melting occurred mostly when there was overcast and strong atmospheric radiation. Radiosonde observations reveal frequent inversions, with comparatively high cloud temperatures. Temporary breaks in the overcast were frequently accompanied by freezing at the surface even though direct solar radiation was relatively larger in such periods.

In order to investigate the role of radiative heat in melting, we have examined the radiation data for clear and overcast conditions at T-3 during July 1958. From measurements of the incoming solar and atmospheric (back) radiation, assuming an albedo of 60 percent which is probably representative of the melting pack ice, it was found (table 2) that on 6 clear days the net radiation averaged +76 ly. day^{-1}. On 9 overcast days it averaged +147 ly. day^{-1}—an increase by a factor of about 2 providing the albedo is unchanged. The radiation data, as presented here, lend some support in explaining these observations made by Untersteiner and Badgley [16]. However, a full explanation would require some idea of the rates of evaporation and turbulent heat exchange in the boundary layer.

There is also an additional point of interest. In view of the observed refreezing of the surface with clear skies, it is rather surprising that the net radiation should be positive. An examination of the data revealed that an albedo of 72 percent or higher would be required in order to have a negative net radiation with clear skies. This seems excessive. It seems reasonable that if freezing of the surface occurs with a positive radiation balance, either one of two things is happening. Either the total heat budget is *negative* because of losses by evaporation and turbulence and therefore refreezing of the surface occurs; or, the total heat budget is *positive* and the "surplus" energy is used in melting just below the surface while freezing continues on the surface. The latter may be possible as the ice is partially transparent to solar radiation and opaque to the longer wavelengths of terrestrial origin. In order to present a realistic model of the processes involved, additional field studies are desirable.

TABLE 2.—*Thermal energy exchange at the surface of Arctic sea-ice during clear, overcast, and average sky conditions as determined from measurements of incident solar and atmospheric (back) radiation at T–3, assuming an albedo of 60 percent and ice surface temperature of 0° C.*

	July 1958		
	Clear sky condition, ≤1-tenth sky cover (on 6 days)	Overcast sky condition, 10-tenths sky cover (on 9 days)	Average sky condition, 6.7-tenths sky cover (31 days)
Incident solar radiation (ly. day^{-1})	643	401	524
Reflected solar radiation (assuming an albedo of 60 percent) (ly. day^{-1})	386	241	314
Ice surface radiation (ly. day^{-1})	653	653	653
Atmospheric (back) radiation (ly. day^{-1})	472	640	578
Return (percent)	72	98	88
Net radiation (ly. day^{-1})	+76	+147	+135

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REFERENCES

1. N. N. Briazgin, "K Voprosu ob Al'bedo Poverkhnosti dreĭfuîûshchikh l'dov," [On the Question of the Albedo on the Surface of Drifting Ice], *Problemy Arktiki, i Antarktiki* No. 1, 1959, pp. 33–39.
2. A. P. Crary, J. L. Kulp, and E. W. Marshall, "Evidences of Climatic Change from Ice Island Studies," *Science*, vol. 122, 1955, pp. 1171–1173.
3. S. Fritz, "Solar Radiation Measurements in the Arctic Ocean," pp. 159–166 of *Proceedings, Polar Atmosphere Symposium, Oslo, July 1956, Part I, Meteorology Section*, Pergamon Press, New York, 1958.
4. M. Giovinetto, Unpublished document, 1958. (Presents measurements of snow density from the surface to −12 meters for the South Pole.)
5. K. J. Hanson, "The Albedo of Sea Ice and Ice Islands in the Arctic Ocean Basin," 1960.
6. K. J. Hanson, "Radiation Measurement on the Antarctic Snowfield, A Preliminary Report," *Journal of Geophysical Research*, vol. 65, No. 3, Mar. 1960, pp. 935–946.
7. G. H. Liljequist, "Energy Exchange of an Antarctic Snowfield, Long-Wave Radiation and Radiation Balance," *Norwegian-British-Swedish Antarctic Expedition, 1949–52, Scientific Results*, vol. II, Part IB, Oslo, 1956, pp. 113–183, (p. 174).
8. G. H. Liljequist, "Energy Exchange of an Antarctic Snowfield, Wind Structure in the Low Layer," *Norwegian-British-Swedish Antarctic Expedition, 1949–52, Scientific Results*, vol. II, Part 1C, Oslo, 1957, pp. 187–233, (p. 224).
9. R. J. List (ed.), *Smithsonian Meteorological Tables*, 6th revised edition, Smithsonian Institution, Washington, D.C. 1951, (see p. 343).
10. F. Loewe, "Études de Glaciologie en Terre Adélie, 1951–52,"

Expéditions Polaires Francaises, No. 9, *Actualités Scientifiques et Industrielles*, No. 1247, Hermann et Cie., Paris, 1956, 159 pp.

11. T. H. MacDonald, Unpublished document, 1959. (Presents the results of temperature response tests on the Eppley pyranometers which were used at United States stations in the Arctic and Antarctic during the International Geophysical Year.)
12. M. Milankovitch, "Mathematische Klimalehre," *Handbuch der Klimatologie*, W. Köppen und R. Geiger, Band I, Teil A, Berlin, 1930, (pp. A30–A31 and table 3).
13. N. P. Rusin, "Radiatsionnyĭ Balans Snezhnoĭ Poverkhnosti v Antarktide," [Radiation Balance of the Snow Cover in the Antarctic], *Informatsionnyĭ Bíulleten' Sovetskoi Antarkticheskoĭ Expeditsiĭ*, No. 2, Leningrad, 1958, pp. 25–30.
14. V. E. Suomi, D. O. Staley, and P M. Kuhn, "A Direct Measurement of Infra-Red Radiation Divergence to 160 mb.," *Quarterly Journal of the Royal Meteorological Society*, vol. 84, No. 360, Apr. 1958, pp. 134–141.
15. H. U. Sverdrup, "Meteorology, Part I, Discussion," *The Norwegian North Polar Expedition with the "Maud", 1918–1925, Scientific Results*, vol. II, Geofysisk Institutt, Bergen, 1933, pp. 1–328.
16. N. Untersteiner and F. I. Badgley, "Preliminary Results of Thermal Budget Studies on Arctic Pack Ice During Summer and Autumn," pp. 85–95 of *Proceedings, Arctic Sea Ice Conference, Easton, Maryland, Feb. 24–28, 1958*, National Research Council, Washington, D.C., Publication No. 598, Dec. 1958.
17. G. N. Yakovlev, "Solar Radiation as the Chief Component of the Heat Balance of the Arctic Ice," pp. 181–189 of *Proceedings, Arctic Sea Ice Conference, Easton, Maryland, Feb. 24–28, 1958*, National Research Council, Washington, D.C. Publication No. 598, Dec. 1958.